California High-Speed Train Project

TECHNICAL MEMORANDUM

Interim Ground Motion Guidelines
TM 2.9.6

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Prepared by PB

for the California High-Speed Rail Authority

System Level Technical and Integration Reviews

The purpose of the review is to ensure:
- Technical consistency and appropriateness
- Check for integration issues and conflicts

System level reviews are required for all technical memoranda. Technical Leads for each subsystem are responsible for completing the reviews in a timely manner and identifying appropriate senior staff to perform the review. Exemption to the system level technical and integration review by any subsystem must be approved by the Engineering Manager.

System Level Technical Reviews by Subsystem:

Systems: NOT REQUIRED
Rick Schmedes Date

Infrastructure: Signature on File 25 Feb 10
Thomas Lee: Date

Operations: NOT REQUIRED
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Paul Mosier Date

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Frank Banko: Date

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ABSTRACT

This technical memorandum provides guidelines for development and implementation of interim ground motions consistent with the California High-Speed Train Project (CHSTP) seismic design criteria. The guidelines contained in this document are based on state-of-the-practice methodologies. Ground motions are required for the design of high-speed train systems and facilities as well as for the evaluation and analyses of seismic hazards such as liquefaction, lateral spreading, dynamic compaction, seismic slope stability, and seismic lateral earth pressures.

Three levels of ground motion analysis are suggested. Preliminary engineering (15% design) will utilize readily available MCE (Maximum Considered Earthquake) data as presented in the California Building Code and ASCE 7. The interim ground motions methods described herein shall be employed for the 30% design. The term “interim” is applied here to clarify that this guidance is intended for use by designers until the final ground motion methods are established. Interim design ground motions shall be prepared corresponding to the project-specific, three-level performance criteria. These performance criteria include: the No Collapse Level (NCL); the Safe Performance Level (SPL), defined as minimal damage that would not jeopardize passenger safety and that can be repaired in a reasonable period of time; and the Operating Performance Level (OPL), defined as no significant interruption to service. Ground motion criteria (earthquake levels) corresponding to these three performance levels in terms of probabilistic and deterministic methods are described herein.

This document presents guidelines for developing interim ground motions that are considered minimum design criteria. As with any guidelines for a long-term project, these ground motion methods will require review and as-needed revisions due to the evolutionary nature of earthquake engineering. This technical memorandum also presents guidelines for developing time histories that will be developed for Soil Structure Interaction (SSI) and dynamic time history analyses. This technical memorandum should be used in conjunction with the other technical memoranda that provide guidelines for the investigation, analysis, and reporting on seismic hazards. It should be noted that a final design ground motion methodology will be established that will be used for final design.

1.0 INTRODUCTION

1.1 PURPOSE OF TECHNICAL MEMORANDUM

The purpose of this technical memorandum (TM) is to provide guidelines to be used in developing interim seismic design ground motions consistent with design and operating performance criteria and the current standard of practice in California. It is critical that these guidelines be followed to promote consistency across project segments designed by different design teams, to reduce potential discrepancies, and resolve inconsistencies between ground motions generated by the design teams. It is the intent of these guidelines to serve as guidance for design teams in advancing the preliminary design. This TM shall be used for the 30% design. A final ground motion TM will provide guidelines to be used for final design.

1.2 STATEMENT OF TECHNICAL ISSUE

A three-tiered ground motion model is not presently available that corresponds to the performance criteria recommended for the CHSTP. Maximum Considered Earthquake (MCE) ground motion values are available from the USGS but do not meet the three performance criteria. Further, as the methods of earthquake engineering and ground motion analysis continue to evolve, the final methodology that will meet the needs of a project to be constructed and in operation several years from now is a difficult target. Interim ground motion development methods are provided herein that will provide guidance for all three performance criteria.

1.3 GENERAL INFORMATION

1.3.1 Definition of Terms

The following technical terms and acronyms used in this document have specific connotations with regard to California High-Speed Train system.

Attenuation Relationship:	Semi-empirical relationship to predict ground motions from a specific seismic source and event.
Design Basis Earthquake (DBE):	Greater of (1) ground motions having a 10% probability of exceedance in 100 years, or (2) the deterministic median plus ½ sigma ground motions from the maximum characteristic earthquake from Class A seismic sources as defined by the California Geological Survey (CGS).
Design Life:	The projected period of time for which a design element will perform under normal loading and environmental conditions under a particular maintenance regimen and meeting minimum specifications before replacement or major rehabilitation is expected.
Design Method:	Load and Resistance Factor Design (LRFD) methods are preferred for force based structural and geotechnical design. Performance based design to be used for MCE and DBE structural design.
Directivity and Near Source Effects:	The effects of direction of fault rupture and closeness to the fault on ground motions.
Lower-level Design Basis Earthquake (LDBE):	Seismic ground motions having a 63.2% probability of exceedance in 100 years.

Maximum Considered Earthquake (MCE):	Seismic ground motions consistent with the current California Building Code (CBC) and ASCE 7-05 i.e., a 2% probability of exceedance in 50 years (or equivalently, 4% in 100 years) with deterministic limits as described in the CBC.
Performance Based Design:	A design based on specific performance criteria in addition to building code based safety criteria.
Performance Criteria:	No Collapse Performance Level (NCL) for which no collapse will occur under MCE. Safety Performance Level (SPL) for which the system shall have repairable damage under DBE. Operating Performance Level (OPL) for which the system shall be designed such that the trains can operate at their optimum speed under LDBE.
Response Spectrum:	The response of damped single degree of freedom oscillators to an earthquake time history.
Seismic Source Model:	The geographic distribution of potential seismic sources that could affect the seismic ground motions at a particular site.
Site Effects/Site Class:	The effect of the subsurface soil/rock profile on the seismic ground motions and as classified in the CBC.
Time History:	The values of acceleration, velocity or displacement with time for an earthquake.
Qualified Analyst:	An individual with the knowledge of engineering seismology and at least 5 years of experience in performing site specific deterministic and probabilistic seismic hazard analyses (DSHA and PSHA) in California.

Acronyms

APEFZ ....Alquist-Priolo Earthquake Fault Zone
ASCE ....American Society of Civil Engineers
Authority...........California High-Speed Rail Authority
BSO ....Basic Safety Objective
CBC ....California Building Code
CGS ....California Geological Survey
CHSTP.............California High-Speed Train Project
DBE ....Design Base Earthquake
DE....................Design Earthquake
DSHA...............Deterministic Seismic Hazard Analysis
FEE..................Functional Evaluation Earthquake
FER..................Fault Evaluation Report
FRA..................Federal Railroad Administration
GMA.................Ground Motion Analysis
GMPE ....Ground Motion Prediction Equation
HSR ....High-Speed Rail
HST..................High-Speed Train
LDBE ....Lower-level Design Basis Earthquake
LRFD ....Load Resistance Factor Design
MCE.................Maximum Considered Earthquake
MPH/mph ....Miles per hour
NGA.................Next Generation of Attenuation
OPL..................Operability Performance Level
PGA ....Peak Ground Acceleration
PGV ....Peak Ground Velocity
PSHA ....Probabilistic Seismic Hazard Analysis
PMT ....Program Management Team
SDC ....Seismic Design Criteria
SEE..................Safety Evaluation Earthquake
SHA ....Seismic Hazards Analysis
SPL ....Safety Performance Level
SRSS ....Square Root of Sum of Squares
SSI ....Soil Structure Interaction
TM....................Technical Memorandum
USGS..............United States Geological Survey
V_{S30} ....Average Shear wave velocity for the upper 100 feet of ground

1.3.2 Units

The California High-Speed Train Project will use U.S. Customary Units consistent with guidelines prepared by the California Department of Transportation and defined by the National Institute of Standards and Technology (NIST). U.S. Customary Units are officially used in the United States, and are also known in the U.S. as "English" or "Imperial" units. In order to avoid confusion, all formal references to units of measure shall be made in terms of U.S. Customary Units. In some cases, U.S. Customary Units are not applicable as some of the analytical equations require inputs in SI units. In those cases, only SI units are mentioned.

2.0 DEFINITION OF TECHNICAL TOPIC

2.1 GENERAL

Seismic ground motions are the input values of ground acceleration, velocity, displacement, response spectra, magnitude, seismic source distance, and duration used in structural and geotechnical design of the system to meet performance criteria.

2.1.1 CHSTP Design Considerations

The risk levels for earthquakes defined in this document are generally consistent with other transit design criteria in California, e.g., BART and Caltrans. It is anticipated that CHSTP design considerations will differ from the BART and/or Caltrans criteria given that performance criteria for the CHSTP are different from available transit criteria.

2.1.2 CHSTP Design Parameters

The most frequently used ground motion design parameters are the peak ground acceleration (PGA), the 5% damped response spectra (in terms of spectral acceleration, velocity and displacement), and the predominant moment magnitude of the design earthquake. In some cases (i.e.: tunnel design), peak ground (or particle at depth) velocity (PGV) and earthquake duration estimates are also needed. Scaled or spectrally matched time histories for DBE and LDBE as well as MCE events will be required for certain structures and geotechnical analyses.

Response spectra at the ground surface for five percent damping for different levels of design earthquakes at various locations in each region along the alignment will be prepared and will be the most used ground motion parameter for this project. Response spectra at other damping levels may be needed for various design components. Response spectra at the bedrock (rock-like materials) level at depth may also be needed if a site response analysis and/or soil-structure interaction analysis (SSI) is required. The methodology for preparing response spectra at the ground surface and at the bedrock level is presented in this technical memorandum.

Spectrally matched time histories that may be used as input for dynamic analysis of structures may be needed at certain locations. Time histories will be needed for performing site response analyses in areas where either Site Class F is identified or where time histories at different depths are needed for Soil-Structure Interaction (SSI) analyses of complex structures. The methodology for preparing spectrally-matched time histories for various components is presented in this technical memorandum.

PGV and earthquake duration estimates are needed to assess wave passage effects on tunnels. The methodology for estimating these parameters are presented in this technical memorandum.

2.1.3 Roles and Responsibilities

It is anticipated that interim ground motions will be developed by the qualified analyst(s) of the design teams for use in preliminary design. To promote overall uniformity of the ground motions and continuity over different segments, strict adherence to this design criteria, ground motion workshops, and intermittent interaction with the PMT will be required.

3.0 ASSESSMENT AND ANALYSIS

3.1 GENERAL

This TM presents guidelines to develop interim ground motions to be used in the 30% design. Guidelines for final ground motions will be prepared for final design. The assessment of seismic ground motions requires development of a seismic source model, establishing site characteristics, selecting appropriate ground motion attenuation relationships and incorporating this information into a suitable computer program to develop site-specific ground motions using probabilistic seismic hazard analysis (PSHA) and/or deterministic seismic hazard analysis (DSHA) methods. These analyses generate peak and spectral acceleration values (response spectra) for ground surface or for an equivalent bedrock outcrop. Rupture directivity and near-source effects shall be added for sites within 16 miles (25 km) of a major fault. The results of these analyses can also be used to develop PGV. In addition, spectrally matched time histories shall be developed based on actual strong motion recordings modified for the specific site conditions and PSHA/DSHA ground motion values.

3.2 SEISMIC PERFORMANCE CRITERIA

Seismic performance shall be considered in the design of high-speed train structures. Performance levels are based on existing HSR systems in seismically active zones and are presented in Technical Memorandum 2.10.4 - Interim Seismic Design Criteria (SDC). The following three levels of design earthquakes shall be considered.

- **Maximum Considered Earthquake (MCE):** Ground motions corresponding to the MCE shall be based on the latest version of ASCE 7. Currently, the ASCE 7-05 defines MCE as the smaller of: (1) 2% probability of exceedance in 50 years (return period of about 2,475 years), and (2) greater of 150% of the median deterministic values from the controlling fault and deterministic lower limit (DLL).
- **Design Basis Earthquake (DBE):** Greater of: (1) ground motions having a 10% probability of exceedance in 100 years (return period of about 950 years), or (2) the deterministic median plus ½ sigma ground motion from the maximum characteristic earthquake from Class A seismic sources as defined by the California Geological Survey (CGS).
- **Lower-level Design Basis Earthquake (LDBE):** Ground motions having 63.2% probability of exceedance in 100 years (return period of about 100 years).

There are three basic performance levels to which high-speed train components will be designed, including:

- **No Collapse Performance Level (NCL):** High-speed train facilities are able to undergo the effects of the Maximum Considered Earthquake (MCE) without collapse. Significant damage may occur that requires extensive repair or complete replacement, yet passengers and personnel are able to evacuate safely.
- **Safety Performance Level (SPL):** High-speed train facilities are able to undergo the effects of the Design Base Earthquake (DBE) with repairable damage and the temporary suspension of train service. However, passengers and personnel can safely evacuate and normal service can resume within a reasonable time frame. Only short-term repairs to structure and track components are expected. Due to the difficulty of inspection and repair, no structural damage should occur below grade.
- **Operability Performance Level (OPL):** The high-speed train system will be able to operate at maximum design speed and safely brake to a stop during a Lower-level Design Basis Earthquake (LDBE). Normal service will resume when track alignments have been inspected and any necessary short term track repairs, such as minor track realignment and grade adjustment, are made. No structural damage is expected.

Refer to TM 2.10.4 - Interim Seismic Design Criteria for guidelines on these performance levels and the corresponding design earthquakes as applied to structures.

Table 3.2-1 presents a matrix relating performance levels with corresponding design earthquakes. The matrix shows the performance level that must be achieved in the design given the design earthquake level. For instance, given the MCE, the design must show that the NCL performance level will be achieved. Likewise, seismic design shall be conducted such that the DBE and LDBE result in SPL and OPL performance, respectively.

Table 3.2-1 – Performance Levels and Design Earthquakes

Design Earthquake Levels \ Performance Levels	OPL	SPL	NCL
MCE	no	no	Yes(2)
DBE	no	Yes(2)	Yes
LDBE	Yes(2)	yes	Yes

Notes: (1) "Yes" or "no" indicates whether the performance level must be met for the given design earthquake level.

(2) Indicates design/analysis to be performed for this combination of ground motion and performance level. Other combinations not marked with a (2) can be evaluated based on inspection.

Design ground motion values are primarily expressed in the form of horizontal and vertical peak and spectral ground accelerations (PGA and response spectra). Other ground motion parameters such as peak ground velocity (PGV), earthquake magnitude, and duration of shaking may also be needed. Spectrally matched time histories from earthquakes having a similar magnitude, duration of shaking and spectral response will be needed for site response and SSI analyses. Site-specific site response analyses using site response computer programs such as SHAKE will be needed for sites classified as Site Class F per classification by ASCE 7.

Site-specific horizontal and vertical response spectra and other ground motion parameters such as PGA and PGV shall be developed using PSHA and/or DSHA methods and strictly following the guidelines presented to maintain consistency across the project's geographic segments. Guidelines are presented for the development of time histories, which may be necessary for the dynamic analyses of structures, estimating slope deformations, SSI analyses, and site response analyses. Additional subsurface investigation will be conducted by the final designer to better characterize the subsurface conditions along the alignment. Appropriate analyses shall be performed to incorporate local site effects. If areas with potentially liquefiable soils are identified along the alignment, appropriate measures shall be taken in order to address the soil liquefaction, generation of pore pressure, and any resulting impacts on the design of ground motions. Site-specific interim ground motion development shall follow the guidelines provided in this technical memorandum. Development of ground motions shall be performed by qualified analyst(s) as defined in this document.

A three-step process shall be used to develop project-specific, interim ground motions:

1. Use the existing seismic source model developed by CGS/USGS for the 2008 National Seismic Hazard Maps (Petersen et. al., 2008).
2. Perform site-specific seismic hazard analyses using probabilistic and deterministic methods

3. Develop interim ground motions in terms of PGA, PGV, response spectra, and time histories.

3.3 EVALUATION METHODS

Interim ground motions in terms of horizontal and vertical response spectra and other ground motion parameters shall be developed as follows.

- Workshops shall be held to present the interim ground motion guidelines.
- Interim ground motions shall be used to develop 30% design.

4.0 SUMMARY AND RECOMMENDATIONS

The context for the development of guidelines for interim ground motions has been described herein. The interim ground motion guidelines are based on current state-of-the-practice methodologies, and have been developed with consideration to existing design methodologies used by transit systems. The interim ground motion guidelines provided in Section 6 are intended for implementation in 30% design until the final ground motion design criteria are established. Specific and detailed methodologies for the development of the interim ground motion design guidelines are presented in order to promote uniformity across project segments.

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6.0 DESIGN MANUAL CRITERIA

6.1 GROUND MOTION GUIDELINES

This TM presents guidelines to develop interim ground motions to be used in the 30% design. Guidelines for final ground motions will be prepared for final design. The assessment of seismic ground motions requires development of a seismic source model, establishing site characteristics, selecting appropriate ground motion attenuation relationships and incorporating this information into a suitable computer program to develop site-specific ground motions using probabilistic seismic hazard analysis (PSHA) and/or deterministic seismic hazard analysis (DSHA) methods. These analyses generate peak and spectral acceleration values (response spectra) for ground surface or for an equivalent bedrock outcrop. Rupture directivity and near-source effects shall be added for sites within 16 miles (25 km) of a major fault. The results of these analyses can also be used to develop PGV. In addition, spectrally matched time histories shall be developed based on actual strong motion recordings modified for the specific site conditions and PSHA/DSHA ground motion values.

6.2 SEISMIC PERFORMANCE CRITERIA

Seismic performance shall be considered in the design of CHSTP structures. Performance levels are based on existing high-speed train systems in seismically active zones and are presented in Technical Memorandum 2.10.4 - Interim Seismic Design Criteria (SDC). The following three levels of design earthquakes shall be considered.

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- **Design Basis Earthquake (DBE):** Greater of: (1) ground motions having a 10% probability of exceedance in 100 years (return period of about 950 years), or (2) the deterministic median plus ½ sigma ground motion from the maximum characteristic earthquake from Class A seismic sources as defined by the California Geological Survey (CGS).
- **Lower-level Design Basis Earthquake (LDBE):** Ground motions having 63.2% probability of exceedance in 100 years (return period of about 100 years).

There are three basic performance levels to which high-speed train components will be designed, including:

- **No Collapse Performance Level (NCL):** CHSTP facilities are able to undergo the effects of the Maximum Considered Earthquake (MCE) without collapse. Significant damage may occur that requires extensive repair or complete replacement, yet passengers and personnel are able to evacuate safely.
- **Safety Performance Level (SPL):** CHSTP facilities are able to undergo the effects of the Design Base Earthquake (DBE) with repairable damage and the temporary suspension of train service. However, passengers and personnel can safely evacuate and normal service can resume within a reasonable time frame. Only short-term repairs to structure and track components are expected. Due to the difficulty of inspection and repair, no structural damage should occur below grade.
- **Operability Performance Level (OPL):** The CHSTP system will be able to operate at maximum design speed and safely brake to a stop during a Lower-level Design Basis Earthquake (LDBE). Normal service will resume when track alignments have been inspected and any necessary short term track repairs, such as minor track realignment and grade adjustment, are made. No structural damage is expected.

Table 6.2.1 presents a matrix relating performance levels with corresponding design earthquakes. The matrix shows the performance level that must be achieved in the design given the design earthquake level. For instance, given the MCE, the design must show that the NCL performance level will be achieved. Likewise, seismic design shall be conducted such that the DBE and LDBE result in SPL and OPL performance, respectively.

Table 6.2-1 – Performance Levels and Design Earthquakes

Design Earthquake Levels \ Performance Levels	OPL	SPL	NCL
MCE	no	no	Yes(2)
DBE	no	Yes(2)	yes
LDBE	Yes(2)	yes	yes

Notes: (1) "Yes" or "no" indicates whether the performance level must be met for the given design earthquake level.

(2) Indicates design/analysis to be performed for this combination of ground motion and performance level. Other combinations not marked with a (2) can be evaluated based on inspection.

Design ground motion values are primarily expressed in the form of horizontal and vertical peak and spectral ground accelerations (PGA and response spectra). Other ground motion parameters such as peak ground velocity (PGV), earthquake magnitude, and duration of shaking may also be necessary. Spectrally matched and/or scaled time histories from earthquakes having a similar magnitude, duration of shaking and spectral response will be needed for site response and SSI analyses. Site-specific site response analyses using site response computer programs such as SHAKE will be needed for sites classified as Site Class F per classification by ASCE 7.

Site-specific horizontal and vertical response spectra and other ground motion parameters such as PGA and PGV shall be developed using PSHA and/or DSHA methods and strictly following the guidelines presented to maintain consistency across the project's geographic segments. Guidelines are also presented for the development of time histories, which may be necessary for the dynamic analyses of structures, estimating slope deformations, SSI analyses, and site response analyses. Ground response analyses shall be performed by designers at specific locations where the site is classified as Site Class F per site classification presented in ASCE 7. Additional subsurface investigation will be conducted by the final designer to better characterize the subsurface conditions along the alignment. Appropriate analyses shall be performed to incorporate local site effects. If areas with potentially liquefiable soils are identified along the alignment, appropriate measures shall be taken in order to address the soil liquefaction, generation of pore pressure, and any resulting impacts on the design of ground motions. Site-specific interim ground motion development shall follow the guidelines provided in this technical memorandum. Development of ground motions shall be performed by qualified analyst(s) as defined in this document.

A three-step process shall be used to develop project-specific, interim ground motions:

1. Use the existing seismic source model developed by CGS/USGS for the 2008 National Seismic Hazard Maps (Petersen et. al., 2008).
2. Perform site-specific seismic hazard analyses using probabilistic and deterministic methods.
3. Develop interim ground motions in terms of PGA, PGV, response spectra, and time histories.

6.3 EVALUATION METHODS

Interim ground motions in terms of horizontal and vertical response spectra and other ground motion parameters shall be developed as follows.

- Workshops shall be held to present the interim ground motion guidelines.
- Interim ground motions shall be used to advance the 30% design level.

6.3.1 Requirements for Interim Ground Motions

The following requirements shall be observed by the designers in order to maintain consistency of the ground motion development methodology along the entire alignment. Any modification to the following requirements shall be properly explained, justified, and approved by the PMT. All the ground motions shall be estimated at the ground surface using the PSHA and DSHA techniques described herein except for sites classified as Site Class F per site classifications presented in ASCE 7. For Site Class F sites, the PSHA and DSHA will be performed for an equivalent bedrock outcrop, and the ground motion at the surface shall be determined through a site-specific ground response analysis (see section 6.3.1.3). The required steps to develop interim ground motions are presented in the form of a flow chart in Figure 6.3-1.

Seismic Source Model

The USGS and CGS have developed a seismic source model for California that includes recommendations by the working groups on California Earthquake Probabilities for both the Bay Area and Southern California that forms the basis for most PSHAs performed in the state.

Designers shall develop the seismic source model for the seismic hazard analyses using the current USGS/CGS (Petersen et al. 2008) model used in developing seismic hazard maps for California. Seismic sources within at least 125 miles (200 km) of the site shall be used in the analyses. This model, along with the source parameters used by the USGS/CGS will be the basis for the interim ground motions. Individual seismogenic sources and aerial sources (to represent background seismicity) shall follow exactly the process used by the USGS/CGS in the current seismic hazard mapping of California. Modifications recommended by the Working Group on California Earthquake Probabilities for both the San Francisco Bay Area and Southern California shall be adopted. The model shall use the same epistemic and aleatory uncertainties as used by the USGS/CGS.

Site Classification

Information about subsurface soil conditions is necessary in order to estimate ground motions at a site and to perform site response analysis in a manner that is consistent across all segments of the high-speed train project. In addition to standard geotechnical parameters such as Atterberg Limits, SPT N-values, and moisture-density values, in-situ shear wave velocity measurements shall be obtained using geophysical methods in deep borings at locations where a site response analysis is needed and/or a structure is located. Additionally, in-situ shear wave velocity measurements shall be obtained using relatively inexpensive tools such as Seismic CPT (SCPT) at locations where ground motion estimates are needed. This shall be performed as part of the geotechnical explorations at the 30% design stage so that these data are available for use in implementing this Interim Ground Motion methodology. These data shall be used to estimate average shear wave velocity in the upper 100 feet (V_{S30}) along the alignment within each region.

V_{S30} shall be calculated from V_S data for discrete depths that was obtained by measurements or correlations using the following equations:

$$V_{S30} = \frac{100}{\sum_{i=1}^{N_{layers}} \left(\frac{d_i}{V_{S,i}} \right)}$$

Where d_i is the thickness of layer i, $V_{S,i}$ is the shear wave velocity of layer i, and N_{layers} is the total number of layers.

If the in-situ shear wave velocity measurement is not performed at a site, V_s values shall be estimated using correlations between standard soil strength parameters and V_s provided in Caltrans Geotechnical Services Design Manual (2009). For sites where V_s data are available for less than 100 feet, methods provided in Caltrans Geotechnical Services Design Manual (2009) shall be used.

In the absence of the site-specific data, V_{S30} may be estimated using existing available maps such as Wills and Clahan (2006). The Wills and Clahan (2006) map (available on the ProjectSolve website) provides median and standard deviation values of V_{S30} for the entire state. The median values shall be used for the analysis. It is emphasized that the Wills and Clahan map shall not be used where site-specific data are available.

Ground Motion Prediction Equations

Ground motion prediction equations (GMPE) shall be the most current widely accepted relationships. Currently, these are the Next Generation of Attenuation (NGA) relationships published in 2008. These relationships include parameter(s) to capture a wide range of common soil profile types, so site specific soil effects are directly accounted for. The Next Generation of Attenuation (NGA) GMPEs for shallow crustal seismic sources shall be used for the probabilistic and/or deterministic seismic hazard analysis. The five NGA equations are Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), and Idriss (2008). For sites with V_{S30} values equal or greater than 1510 feet/sec (460 m/s), all five NGA equations with equal weights shall be used. For all other sites, four NGA equations (excluding equations by Idriss) with equal weights shall be used. For site class F, a site-specific ground response analysis shall be performed.

It is anticipated that the contribution from the Cascadia Subduction Zone (CSZ) shall not be significant on the high-speed train alignment. If the CSZ is included in the seismic source model, a different set of GMPEs will be needed. For CSZ, GMPEs by Youngs et al. (1997), Atkinson and Macias (2009), and Zhao et. al. (2006) shall be used with equal weights.

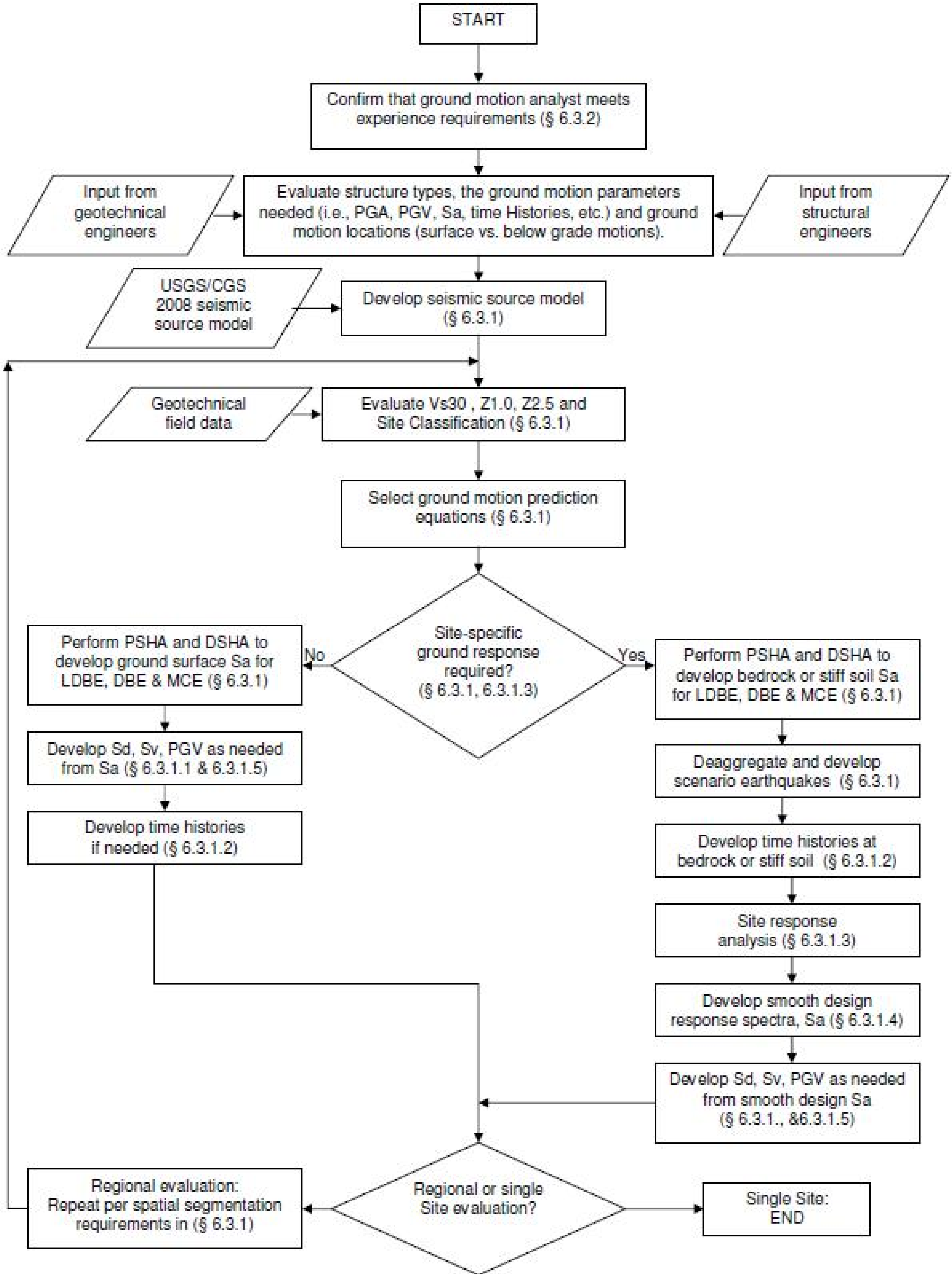

Figure 6.3-1: Flow chart showing required steps to develop interim ground motions

Basin Effects

To account for basin effects, NGA GMPEs by Abrahamson and Silva (2008) and Chiou and Youngs (2008) require estimate of $Z_{1.0}$ [depth in meters where Vs is 3,280 feet/sec (1,000 m/s)] and Campbell and Bozorgnia (2008) requires estimate of $Z_{2.5}$ [depth in km where Vs is 8,200 feet/sec (2,500 m/s)]. There are certain basins in the Los Angeles, Ventura, Salton Sea, and Northern California where these values will be needed for the analyses. If site-specific information for $Z_{1.0}$ is available then it shall be used. The Southern California Earthquake Center (SCEC) Community Fault model provides estimates of these parameters for those areas in the Los Angeles basin. In addition, estimates for these values in these basins may be obtained from Caltrans Seismic Design Criteria Appendix B (http://dap3.dot.ca.gov/shake_stable/references/SDC_Appendix_B_120309.pdf) or using Caltrans ARS online tool (http://dap3.dot.ca.gov/shake_stable/index.php). If the site is outside of these basins and/or site-specific information is not available, then default values of 400 m for $Z_{1.0}$ and 3 km for $Z_{2.5}$ shall be used for all other areas.

Earthquake Recurrence Model

For most seismic sources, the Gutenberg-Richter (G-R) magnitude-frequency relationship (Gutenberg and Richter, 1956), and the Characteristic Model (Schwartz and Coppersmith, 1984) shall be used with one-third and two-thirds weights, respectively. However, for CGS Class A faults, only the Characteristic Model shall be used.

Spatial Segmentation

Because of variation in site-source distances, site conditions and other factors, ground motion values will vary along the alignment within a region. An alignment region shall be divided into a set of sub-regions such that the variations in the ground motions for each level of earthquake shall be less than 20 percent within each sub-region. The results for a point within that sub-region that provides the highest level of ground motion within the segment shall be used. It may be necessary to perform some preliminary parametric analyses to establish the point with the highest ground motion level.

Analysis

Perform probabilistic seismic hazard analysis for each segment using computer programs such as EZ-FRISK (Risk Engineering, 2009), or a similar program. For deterministic seismic hazard analysis, modules within the computer program such as EZ-FRISK may be used or alternatively, available spreadsheets (e.g., from the PEER website) can be used. It is highly recommended that the computer program EZ-FRISK (version 7.36 or later) shall be used for both PSHA and DSHA by all design teams to maintain consistency along the entire alignment. Geometric mean values of ground motions shall be used for both PSHA and DSHA. The NGA relationships do not currently account for variations in ground motion due to rupture directivity and near fault effects. Where a site is within the near fault zone (for this project, the near fault zone is defined as minimum of 16 miles (25 km) from the surface projection of a CGS Class A or B fault) the NGA results need to be adjusted. The latter is particularly important depending on the orientation of a structure relative to a major fault since the long period fault normal motion is significantly higher than the fault parallel motion. Because of the uncertainties inherent in fault orientation, discovery of new faults and more importantly changes in project rail alignment, etc., it may be more appropriate and conservative to use the higher of the fault parallel and fault normal spectra for design unless using two different spectra is shown to be appropriate for the design. It should be noted that the fling effect (velocity pulse) observed in many near fault recordings can be accounted for only in the time history analysis.

Results

Results shall be presented in both graphical and in tabular forms in terms of PGA and smoothed five percent damped site-specific horizontal design fault normal (FN), fault average (FA), and fault parallel (FP) response spectra for a period of up to 10 seconds for the MCE, DBE, and the LDBE for each segment within the region. If the results are controlled by the PSHA then dominant mode magnitudes and distances based on the results of magnitude-distance-epsilon deaggregation analyses shall be presented for at least PGA, and periods of 0.2, 1.0, and 2.0

seconds. If the results are controlled by DSHA, then appropriate magnitude and distances shall be reported for the same spectral periods as mentioned earlier. In addition, five percent damped vertical response spectra shall be developed using the horizontal response spectra and vertical to horizontal (V/H) ratios available in literature such as Abrahamson and Silva (1997) and Campbell and Bozorgnia (2003). A suite of scaled or spectra-matched time histories shall be developed where needed for dynamic structural analyses.

6.3.1.1 Response Spectra and Other Ground Motion Parameters

Horizontal and vertical response spectra, PGA, PGV, and other associated parameters such as magnitude and duration of shaking shall be provided at the ground surface representing free-field conditions. These parameters can be used in the dynamic analyses of structures and in evaluating seismic hazards.

Horizontal response spectra and PGA shall also be developed using the methodology described in Section 6.3.1 for site conditions representing equivalent bedrock outcrop (or for conditions represented by soils at a depth in deep alluvial basins equivalent to a shear wave velocity of about 1,700 feet/sec) at locations where ground response analyses are needed. These parameters will be used to develop time histories for use as input to ground response analyses.

The PSHA does not directly provide the designer with a design earthquake magnitude. For this, a magnitude-distance-epsilon deaggregation analysis shall be performed to evaluate the hazard contribution of various combinations of magnitude and distance consistent with the PSHA ground motions at the site.

Spectral acceleration attenuation relationships are generally based on an assumed damping of the structure of 5%. The design ground motions shall be presented for 5% damping, in general. However, structural behavior during various levels of shaking may vary from this assumed damping coefficient. Where other damping values are needed, methods similar to those developed by Newmark and Hall (1965) shall be used to develop appropriate spectral values from the 5% values described above. Where pseudo-spectral displacements (S_d) or pseudo-spectral velocities (S_v) are needed, they can be calculated from the spectral accelerations (S_a) and period (T) using the following equations from Newmark and Hall (1965):

$$S_d = S_a \cdot \frac{T^2}{4\pi^2} \qquad S_v = S_a \cdot \frac{T}{2\pi}$$

6.3.1.2 Time Histories

Time histories are used in the design of some structures, for estimating soil slope/lateral spreading movements, site specific ground response studies and soil-structure interaction (SSI) analyses.

Time histories shall be selected from available records with similar spectral shape, moment magnitude, distance, site class, and rupture mechanism compared to the design ground motion. The time histories shall have appropriate duration, frequency content, and forward directivity effects when applicable. Many time histories are available in the NGA database at the Pacific Earthquake Engineering Research (PEER) Center website (http://peer.berkeley.edu/nga/). The fundamental period of the structure shall also be considered in selecting the appropriate time histories. Three or seven sets (each set contains two horizontal and one vertical) of good records shall be selected and scaled or spectra matched to the response spectrum being considered. The spectral matching shall be done using time domain techniques such as Abrahamson (1998) and frequency domain techniques shall not be permitted. The scaling or spectra matching shall be done such that the square root of sum of squares (SRSS) criteria provided in Chapter 16 of ASCE 7-05 shall be met. When fault normal and fault parallel time histories are needed, the recorded time histories shall be rotated to either fault normal and fault parallel orientations or preferably to the major and minor principal axes prior to spectra matching. The major and minor principal axes correspond to the directions which result in maximum and minimum spectral displacement at the fundamental period of the structure under consideration. In addition, time histories for the ground response analysis, shall be developed for equivalent bedrock outcrop conditions. The statistical correlation coefficient between the two horizontal components of a scaled or spectrally matched time history shall not exceed 30%. All time histories shall be baseline corrected in the time domain.

For SSI analyses, where time histories are needed at a certain depth from the ground surface, convolution or deconvolution ground response analysis procedures as explained in the following section shall be used by the designers to develop input time histories for the SSI analyses. For the convolution and deconvolution analyses, three or seven sets of time histories at the bedrock (or at a depth in deep alluvial basins equivalent to a shear wave velocity of about 1,700 feet/sec) and at the ground surface, respectively, shall be developed and used.

Spatial incoherency in the ground motions for long structures such as long tunnels, bridges, or viaducts may be considered. If this ground motion incoherency is an important parameter for the design, the designer shall work closely with an experienced engineering seismologist to identify the relevant factors contributing to ground motion incoherence at a specific site and to develop appropriate time histories.

6.3.1.3 Site Specific Ground Response Analyses

Ground response analyses are either performed from a depth to the ground surface (convolution) or from the ground surface to a depth (deconvolution). In general, convolution is performed to develop design response spectra at the ground surface. However, for SSI analyses, either convolution or deconvolution may be performed. There have been a number of computer programs developed to generate site specific ground motions by modeling the soil profile and inputting ground motions at bedrock or deep in the soil profile, e.g., SHAKE91 (Idriss and Sun, 1992), DMOD, DEEPSOIL, OpenSees, FLAC etc. However, for most ground conditions, standardized ground response factors, such as those incorporated in the NGA relationships, are more appropriate because they are based on a combination of actual ground motion records, research studies, and geotechnical experience. Nevertheless, site response analyses are appropriate or even required for certain conditions including Site Class F soil profiles and input into SSI analyses. Site response analyses may also be necessary to estimate soil or rock shear strain for use in seismic ovaling and racking analysis of tunnels.

These analyses are performed by selecting appropriate scaled or spectra-matched rock or firm soil time histories and propagating them either upwards (convolution) or downwards (deconvolution) through a soil profile that accounts for the dynamic properties of the soil. Soil profile(s) at a site shall be developed using the shear wave velocity profile obtained during the geotechnical field investigation program. For convolution, the base of the site response model shall be taken as the top of bedrock, or where the shear wave velocity becomes 1,700 feet per second (when bedrock is very deep). For deconvolution, the time histories shall be applied at the ground surface. A total of three or seven time histories shall be used when site response analysis is performed to develop design response spectra at the surface. When site response analysis is performed to develop time histories for SSI analyses, three or seven sets (each set containing two horizontal and one vertical) of time histories shall be used. Reliable shear wave velocities of the soil profile are essential for this as well as a good assessment of the strain-dependent modulus and damping characteristics of the soils. Low-strain shear wave velocity values for each soil layer shall be estimated using either the results of direct measurement with geophysical methods (such as downhole, crosshole, seismic CPT, etc.) or using available correlations between SPT N-values or undrained shear strength and shear wave velocity. Evaluation of shear wave velocity by direct measurement is strongly preferred over correlation.

Ground surface time histories resulting from site response analyses may be used either as direct input to dynamic time history analysis of structures (time history case), or to develop a design response spectrum that is used in frequency domain-based analysis of structures (response spectrum case). For the time history case, if three time histories are used, the maximum structural response shall be used for the design and if seven time histories are used, the average structural response shall be used for the design. The procedure for developing a design ground surface response spectrum from site response analysis is described in Section 6.3.1.4.

The selection of soil dynamic properties in the form of strain-dependent shear modulus ratio and damping curves is critical in site response analysis. For the 30% design, available curves such as by Seed et al. (1986), Vucetic and Dobry (1991), Idriss and Sun (1992), Darendelli and Stokoe (2001) and Roblee and Chiou (2004) shall be used as applicable.

Ground response analysis for Site Class F (as defined in ASCE 7) shall be performed using both equivalent-linear (such as SHAKE) and non-linear (such as DMOD, DEEPSOIL, FLAC or OpenSees) methods. The design response spectra shall be constructed by enveloping the spectra resulting from separate analyses using these two methods.

Vertical ground motions in terms of design response spectra shall be developed using the horizontal ground motions and vertical to horizontal (V/H) ratios estimated using Abrahamson and Silva (1997) and Campbell and Bozorgnia (2003) relationships. An arithmetic average of V/H ratios from these two relationships shall be used. Site response analysis in vertical direction for the purpose of developing design response spectra is not a reliable method, and therefore, shall not be used except for the case when SSI analyses are to be performed and vertical time histories are needed at certain depth. For vertical site response analyses, P-wave velocity estimated from the strain compatible Vs values obtained from the horizontal site response shall be used for the soils layers above groundwater. For soil layers below groundwater, P-wave velocity of 5,000 feet/sec shall be used. These P-wave velocities will be used to determine an elastic constrained modulus that shall be used in place of the shear modulus in equivalent linear site response analyses. The damping used in vertical site response analyses shall be taken equal to the strain compatible damping obtained from the horizontal site response analysis for all layers. When performing vertical site response using the computer program SHAKE with prescribed constrained modulus and damping, the number of iterations should be set to one (1) so that the program does not attempt to iterate to different values of modulus and damping.

6.3.1.4 Development of Design Surface Response Spectrum

Several soil models may be developed for a single site to accommodate the site condition variation and the uncertainty in parameters selection. The site response analysis based on each combination of a soil model and an input bedrock/outcrop ground motion time history will produce a surface ground motion time history and therefore a surface response spectrum. The ratio of the ordinate of the surface response spectrum to the base input ground motion response spectrum (response spectrum of the input outcrop motion) at each period shall be obtained. This ratio of response spectra (RRS) indicates the amplifying (or de-amplifying) effect of the soil profile. The smooth target bedrock input response spectrum shall be multiplied by the RRS from each site response analysis to develop RSS-based ground surface spectra. If three input time histories were used in the site response analysis, the design response spectrum shall be taken as the envelope of the RSS-based ground surface spectra. If seven or more input time histories were used, the design response spectrum shall be taken as the arithmetic average of the RSS-based ground surface spectra. The design spectrum shall be modified to be relatively smooth by connecting adjacent peaks (with a trough between) with a straight line from peak to peak (see example in Figure 6.3-2).

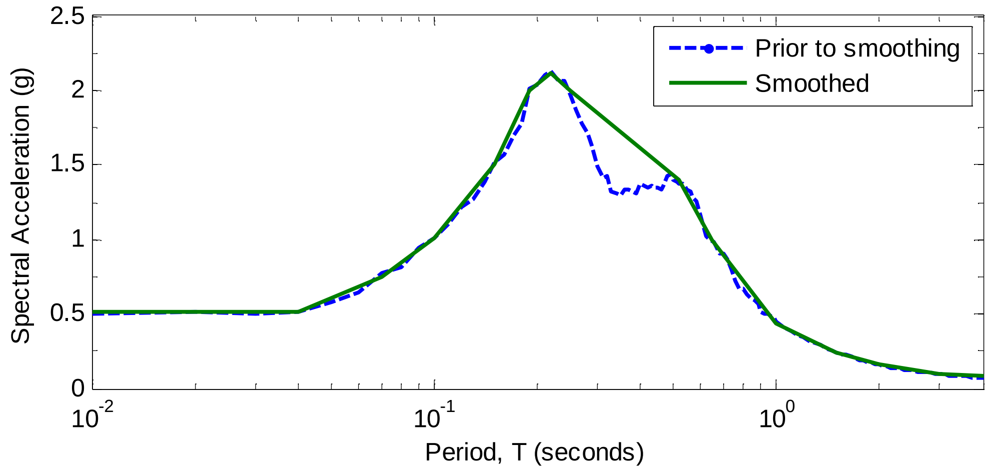

Figure 6.3-2 Example of Smoothing

The spectral values from a ground response analysis shall be taken as less than 80% of the Site Class D values (evaluated based on Section 6.3.1 procedures) or, for liquefiable soil conditions 80% of Site Class E values (based on Section 6.3.1)in the ASCE 7 for the MCE level. For the DBE and the LDBE levels, the spectral values from a ground response analysis shall not fall below 80% of the spectral values for those levels developed assuming a Site Class D or for liquefiable conditions 80% of the spectral values assuming Site Class E.

6.3.1.5 Peak Ground Velocity

Peak ground velocity (PGV) shall be estimated using the following equation (Anderson et. al., 2008):

$$\ln(PGV) = 3.97 + 0.94\ln(S_1) + 0.013[\ln(S_1) + 2.93]^2 + 0.063M$$

where PGV is in units of cm/s, S_1 is the spectral acceleration at T = 1 sec in units of g, and M is the earthquake magnitude.

6.3.2 Qualifications for Ground Motion Analyst

Design ground motion development shall be performed by a qualified individual and/or firm with experience as a “qualified analyst”. The qualified analyst shall be knowledgeable of engineering seismology and shall have 5 years (minimum) experience in performing site specific deterministic and probabilistic seismic hazard analyses (DSHA and PSHA) in California. This experience shall include performing PSHA analyses to develop design ground motions for at least five California public school or hospital projects in the last five years. The school or hospital PSHA work must have been performed within the past five years and reviewed and approved by the California Geological Survey (CGS) or the California Office of Statewide Health Planning and Development (OSHPD). The qualified analyst shall have experience performing PSHA analyses using commercially available or proprietary software that incorporates a logic tree to account for epistemic uncertainty.